

PHOTOMETRIC AND SPECTROSCOPIC FOLLOW-UP OF OPTICAL COUNTERPARTS OF X-RAY SOURCES IN THE RASTYC SAMPLE

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Abstract The cross-correlation between the ROSAT all-sky survey ($\sim 150\,000$ sources) and the Tycho mission ($\sim 1\,000\,000$ stars) catalogs has selected about 14 000 stellar X-ray sources (RasTyc sample, Guillout et al. 1999).

About 200-300 stars have been spectroscopically observed at high resolution both in the $H\alpha$ and $\text{LiI } \lambda 6708$ regions with ELODIE and AURELIE spectrographs of the OHP (Observatoire de l'Haute Provence, France). The aim was to classify the RasTyc star sample in terms of age and chromospheric activity level and to detect eventual binary systems.

Photometric and spectroscopic follow-up observations of a RasTyc sub-sample composed of particularly interesting objects (binaries and very young stars) has been performed with the 91-cm telescope of the Catania Astrophysical Observatory.

In this work we present some results of this monitoring. In particular, we have obtained good radial velocity curves and solved for the orbits of three SB2 and three SB1 spectroscopic binaries. In addition, for near all sources we have detected a photometric modulation ascribable to photospheric surface inhomogeneities and chromospheric $H\alpha$ line variation.

Keywords: Stars: binaries: spectroscopic, Stars: fundamental parameters, Stars: X-ray, Stars: activity

Introduction

From the ROSAT All-Sky Survey ($\simeq 150\,000$ sources) and the TYCHO catalogs ($\simeq 1\,000\,000$ stars) Guillout et al. (1999) selected about 14 000 optical counterparts of stellar X-ray sources, the so-called RasTyc sample. The high X-ray emission level of these sources is compatible with young stars in the solar neighborhoods, or with close binaries of the RS CVn and BY Dra classes, for which the high magnetic activity level is due to the synchronization of rotational and orbital periods. The knowledge of the incidence of binaries in this sample is of paramount importance for studying the recent local star formation history. We thus have started a spectroscopic observation campaign aimed at a deep characterization of a representative sub-sample of the RasTyc population. As a matter of fact, the high-resolution spectroscopic observations allow to derive spectral types and luminosity classes, to infer ages (by means of Lithium abundance) and to single out spectroscopic binaries. In addition, chromospheric activity levels (from $H\alpha$ emission) and rotational velocities (from Doppler broadening), can be also determined.

In this work we report on the discovery of three single-lined (SB1) and three double-lined (SB2) late-type binaries, which have been observed with the 193-cm telescope of the *Observatoire de Haute Provence* (OHP) and the 91-cm telescope of the Catania Astrophysical Observatory (OAC). For these binaries we have obtained good radial velocity curves and orbital solutions. An accurate spectral classification has been also performed and the projected rotational velocity $v \sin i$ has been measured for all stars. The $H\alpha$ emission and the $\text{LiI } \lambda 6708$ line have been used to infer the chromospheric activity level and the lithium content, respectively.

1. Observations and reduction

Spectroscopy

Spectroscopic observations have been obtained at the *Observatoire de Haute Provence* (OHP) and at the *M.G. Fracastoro* station (Serra La Nave, Mt. Etna, 1750 m a.s.l.) of the Catania Astrophysical Observatory (OAC).

At OHP we observed in 2000 and 2001 with the ELODIE echelle spectrograph connected to the 193-cm telescope. The 67 orders recorded by the CCD detector cover the 3906-6818 Å wavelength range with a resolving power of about 42 000 (Baranne et al. 1996). The ELODIE spectra were automatically reduced on-line during the observations and the cross-correlation with a reference mask was produced as well.

The observations carried out at Catania Observatory have been performed in 2001 and 2002 with the REOSC echelle spectrograph at the 91-cm telescope. The spectrograph is fed by the telescope through an optical fiber (UV

- NIR, 200 μm core diameter) and is placed in a stable position in the room below the dome level. Spectra were recorded on a CCD camera equipped with a thinned back-illuminated SITe CCD of 1024×1024 pixels (size $24 \times 24 \mu\text{m}$). The echelle crossed configuration yields a resolution of about 14 000, as deduced from the FWHM of the lines of the Th-Ar calibration lamp. The observations have been made in the red region. The detector allows us to record five orders in each frame, spanning from about 5860 to 6700 Å.

The OAC data reduction was performed by using the ECHELLE task of IRAF¹ package following the standard steps: background subtraction, division by a flat field spectrum given by a halogen lamp, wavelength calibration using the emission lines of a Th-Ar lamp, and normalization to the continuum through a polynomial fit.

Photometry

The photometric observations have been carried out in 2001 and 2002 in the standard *UBV* system with the 91-cm telescope of OAC and a photon-counting refrigerated photometer equipped with an EMI 9789QA photomultiplier, cooled to -15°C . The dark noise of the detector, operated at this temperature, is about 1 photon/sec.

For each field of the *RasTyc* sources, we have chosen two or three stars with known *UVB* magnitudes to be used as local standards for the determination of the photometric instrumental “zero points”. Additionally, several standard stars, selected from the list of Landolt (1992), were also observed during the run in order to determine the transformation coefficients to the Johnson standard system.

A typical observation consisted of several integration cycles (from 1 to 3, depending on the star brightness) of 10, 5, 5 seconds, in the *U*, *B* and *V* filter, respectively. A 21-arcsecond diaphragm was used. The data were reduced by means of the photometric data reduction package PHOT designed for photoelectric photometry of Catania Observatory (Lo Presti & Marilli 1993). Seasonal mean extinction coefficient for Serra La Nave Observatory were adopted for the atmospheric extinction correction.

2. Results

Radial velocity and photometry

The radial velocity (RV) measurements for the ELODIE data have been performed onto the cross-correlation functions (CCFs) produced on-line during the data acquisition.

Radial velocities for OAC spectra were obtained by cross-correlation of each echelle spectral order of the *RasTyc* spectra with that of bright RV standard

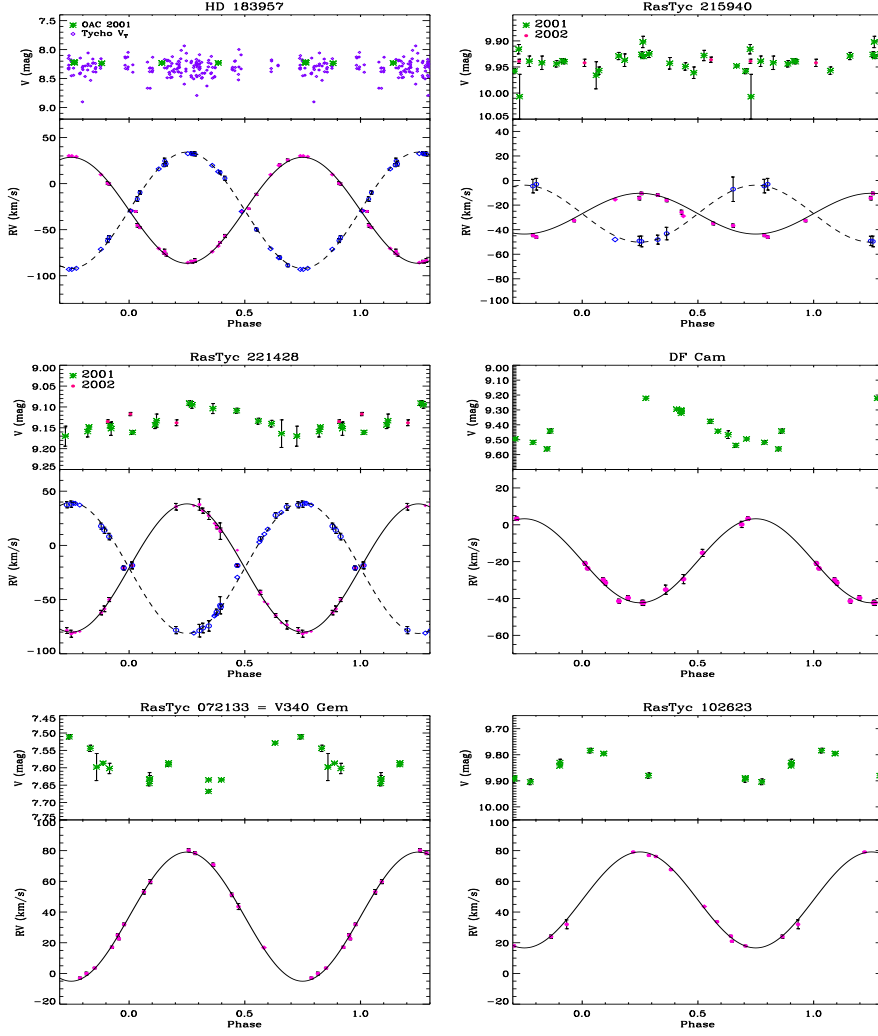


Figure 1. Radial velocity curves (dots= OAC data, diamonds= ELODIE data) of the new six RasTyc binaries. For the three SB2 systems we used filled and open symbols for the primary (more massive) and secondary components, respectively. The circular solutions are also represented with solid and dashed lines for the primary and secondary components, respectively. The contemporaneous V photometry is displayed, as a function of the orbital phase, on the top panel of each box.

stars. For this purpose the IRAF task FXCOR, that computes RVs by means of the cross-correlation technique, was used.

Table 1. Orbital parameters of the new binaries.

<i>RasTyc</i>	<i>Name</i>	P_{orb} (days)	γ (km s ⁻¹)	k (P/S) (km s ⁻¹)	$M \sin^3 i$ (P/S) (M _⊙)
193137	HD 183957	7.954	−29.0	57.5/63.1	0.758/0.691
215940	OT Peg	1.748	−27.0	16.6/23.2	0.007/0.005
221428	BD+33 4462	10.12	−20.9	59.2/60.4	0.905/0.887
040542	DF Cam	12.60	−19.5	22.8	SB1
072133	V340 Gem	36.20	+37.0	42.1	SB1
102623	BD+38 2140	15.47	+47.4	31.3	SB1

The wavelength ranges chosen for the cross-correlation excluded the H α and Na I D₂ lines, which are contaminated by chromospheric emission and have very broad wings. The spectral regions heavily affected by telluric lines (e.g. the O₂ lines in the λ 6276 – λ 6315 region) were also excluded.

The observed RV curves are displayed in Fig. 1, where, for SB2 systems, we used dots for the primary (more massive) components and open circles for the secondary (less massive) ones. We initially searched for eccentric orbits and found in any case very low eccentricity values (e.g. $e = 0.010$ for HD 183957, $e = 0.030$ for RasTyc 221428). Thus, following the precepts of Lucy & Sweeney (1971), we adopted $e = 0$. The circular solutions are also represented in Fig. 1 with solid and dashed lines for the primary and secondary components, respectively.

The orbital parameters of the systems, orbital period (P_{orb}), barycentric velocity (γ), RV semi-amplitudes (k) and masses ($M \sin^3 i$), are listed in Table 1, where P and S refer to the primary and secondary components of the SB2 systems, respectively.

With the only exception of HD 183957, for which any modulation is visible neither in OAC data nor in TYCHO V_T magnitudes, all sources show a photometric modulation well correlated with the orbital period, indicating a high degree of synchronization. The low amplitude of RasTyc 215940's light curve and the very low values of $M \sin^3 i$ imply a very low inclination of orbital/rotational axis.

Spectral type and $v \sin i$ determination

The projected rotational velocity, $v \sin i$, was measured using the ELODIE CCFs and the calibration relation between CCF width and $v \sin i$ proposed by Queloz et al. (1998) and is reported in Table 2. The lowest rotation rate ($v \sin i \simeq 4$ km s⁻¹) has been detected for both components of HD 183957, which display also the lowest H α activity among the six sources.

Table 2. Physical parameters of the new binaries.

<i>RasTyc</i>	<i>Name</i>	$v \sin i$ (P/S) (km s^{-1})	<i>Sp. Type</i> (P/S)	$B - V$	W_{LiI} (P/S) (mÅ)
193137	HD 183957	4.0/4.4	K0V/K1V	0.84	< 10
215940	OT Peg	9.2/9.4	G8V/K3-4V	0.79	60/–
221428	BD+33 4462	9.7/26.5	F8V/K0III-IV	0.70	–/15:
040542	DF Cam	35	K2III	1.14	—
072133	V340 Gem	40	G8III	0.83	70
102623	BD+38 2140	11.5	K1IV	1.03	40

For SB1 systems observed with ELODIE we have determined effective temperatures and gravity (i.e. spectral classification) by means of the TGMET code, available at OHP (Katz et al. 1998). We have also used ROTFIT, a code written by one of us (Frasca et al. 2003) in IDL (Interactive Data Language, RSI), which simultaneously find the spectral type and the $v \sin i$ of the target by searching, into a library of standard star spectra, for the standard spectrum which gives the best match (minimum of the residuals in the difference) of the target one, after the rotational broadening. As a standard star library, we used a sub-sample of the entire TGMET list, composed of 87 stars well distributed in effective temperature and gravity and in a suitable range of metallicities. The standard star spectra were retrieved from the ELODIE Archive (Prugniel & Soubiran 2001). The ROTFIT code was also applied to the OAC spectra, using standard star spectra acquired at OAC with the same instrumental setup. This was especially advantageous for DF Cam, for which we have no ELODIE spectrum. We have performed an accurate spectral classification also for the components of SB2 systems, thanks to another IDL code made by us, COMPO2, which searches for the best combination of standard-star spectra able to reproduce the observed spectrum of the SB2 system. We give the radial velocity and $v \sin i$ of the system components as input parameters and the code finds, for the selected spectral region, the spectral types and fractional flux contributions which better reproduce the observed spectrum, i.e. which minimize the residuals in the collection of difference, *observed* – *synthetic* spectra. Results for different ELODIE orders from blue to red wavelengths are in very good agreement (Fig. 2).

We found only two binaries composed of main sequence stars, while the remaining systems contain an evolved star (giant or sub-giant) and can be classified as new RS CVn systems (see Table 2).

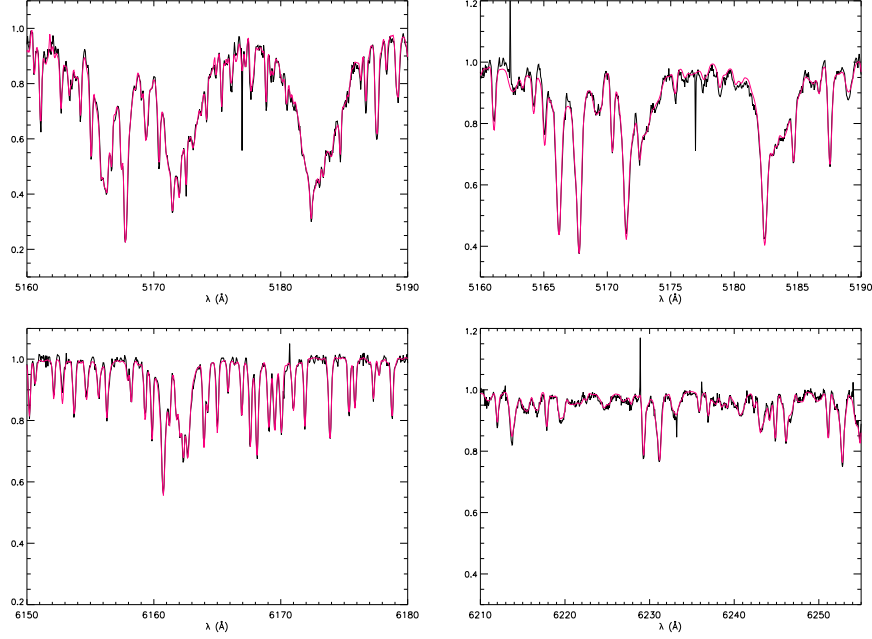


Figure 2. **Left panels)** Observed ELODIE spectrum of the SB2 binary HD 183957 (thick black lines) in the MgIb (top) and the λ 6170 Å (bottom) spectral regions together with the “synthetic” spectrum over-plotted with a red line. The latter was built up as the weighted sum of two standard star spectra (K0 V for the primary and K1 V for the secondary one) broadened at the $v \sin i$ of the respective component and Doppler-shifted according to the orbital solution and the phase of the observation ($\phi = 0.36$). The fractional flux contribution of the primary component is 0.62 and 0.58 at 5170 and 6170 Å, respectively. **Right panels)** Observed ELODIE spectrum of RasTyc 221428 (thick black lines) in the MgIb (top) and in the λ 6230 Å (bottom) regions. The “synthetic” spectrum (F8 V + K0 III-IV) is displayed with red lines in the same boxes. The excellent agreement of the observed and synthetic spectra is apparent.

H α emission and Lithium content

The H α line is one of the most important and easily accessible indicators of chromospheric activity. Only the very active stars show the H α line as an emission feature always above the local continuum, while in the spectra of less active objects only a filled-in absorption line is observed. The detection of the chromospheric emission contribution filling in the line core is hampered by the complexity of the observed spectra of double-lined binaries in which the spectral lines of both components, shifted at different wavelengths according to the orbital phase, are simultaneously seen. Therefore a comparison with an “inactive” template, composed of two stellar spectra mimicking the two system

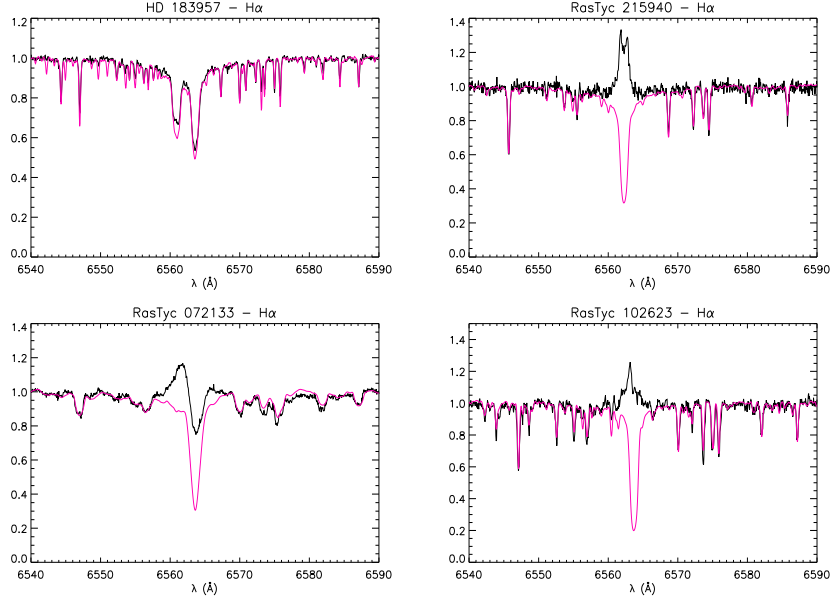


Figure 3. ELODIE spectra of HD 183957, RasTyc 215940, 072133, and 102623 in the $H\alpha$ region (black lines). The inactive templates built up with rotationally broadened ELODIE Archive spectra are displayed with red lines. The two components of HD 183957 show only a small filling of their $H\alpha$ profiles, while RasTyc 072133 displays a double-peaked $H\alpha$ emission profile. RasTyc 215940 and 102623 display instead a pure emission $H\alpha$ profile.

components in absence of activity, is needed to emphasize the $H\alpha$ chromospheric emission.

The inactive templates have been built up with rotationally broadened ELODIE archive spectra (HD 165341, K0 V and HD 10476, K1 V for the primary and secondary component of HD 183957, respectively; γ Cep, K1 IV for 102623; δ Boo, G8 III for 072133; HD 17382, K1 V for 215940) or with OAC spectra of α Ari (K2 III), for DF Cam, acquired during the observing campaigns.

The two components of HD 183957 show only a small filling of their $H\alpha$ profiles (Fig. 3), i.e. a moderate activity level. This is in agreement with the low $v \sin i$ values indicating a system composed of two early-K stars which are probably synchronously rotating with a period of about 8 days. The filling in of the $H\alpha$ line of both components of HD 183957 is lower than that found for HD 166 (Biazzo et al. 2004), a K0 V star belonging to the Local Association (100-300 Myrs) with a rotation period of 6.2 days.

The other RasTyc stars display $H\alpha$ emission profiles with a variety of shapes, going from a simple symmetric emission profile (102623) to a strong emission

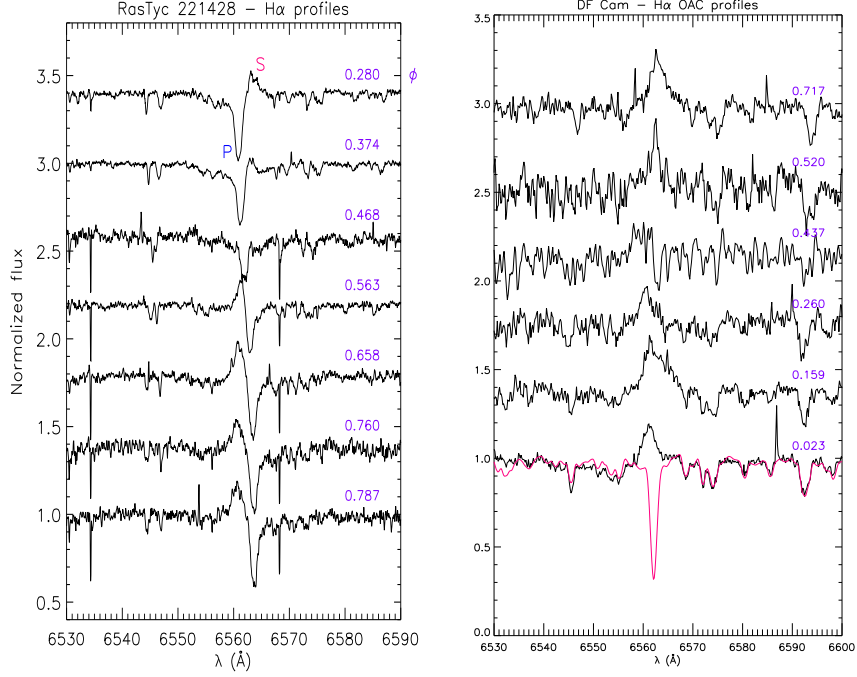


Figure 4. **Left panel)** Sample of ELODIE spectra of RasTyc 221428 in the H α region at different orbital phases. The cooler K0 III-IV component shows a H α line always in emission with a stronger intensity around phase 0.7, while the hotter F8 V component displays a normal H α absorption profile. **Right panel)** OAC spectra of DF Cam in the H α region at different orbital phases. The H α intensity and shape varies with the orbital/rotational phase.

line with central reversal (215940). It has been also observed a very broad, complex feature with a filled-in core and an emission blue wing (072133). A H α profile similar to that displayed by the latter star has been sometimes observed in some long-period RS CVn's, like HK Lac (e.g. Catalano & Frasca 1994). RasTyc 072133 was classified as a semi-regular variable after Hipparcos, but it displays all the characteristics of a RS CVn SB1 binary.

The ELODIE spectra of RasTyc 221428 in the H α region show that the cooler K0 III-IV component displays a H α line always in emission with a stronger intensity around phase 0.7 (Fig. 4). The OAC spectra of DF Cam always display a pure H α emission line, whose intensity varies with the orbital/rotational phase (Fig. 4). Similarly to RasTyc 072133, DF Cam, considered as a semi-regular variable after Hipparcos photometry, is very likely an active binary of the RS CVn class.

The equivalent width of the lithium $\lambda 6708$ line, EW_{Li} , was measured on the ELODIE spectra. For the three sources for which we were able to detect and

measure EW_{Li} (Table 2), we have deduced a lithium abundance, $\log N(\text{Li})$, in the range 1.3–1.8, according to Pavlenko & Magazzu’ (1996) NLTE calculations. Such values of lithium abundance indicate ages of at least a few hundreds Myrs, so that the X-ray emission and the fairly strong $H\alpha$ chromospheric activity detected in these systems should be essentially the effect of the rather fast stellar rotation due to the spin/orbit synchronization.

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Notes

1. IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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